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J. Nilsen, Y. Li, J. Dunn, A. L. Osterheld,
A. Ryabtsev, S. Churilov

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Joseph Nilsen, Yuelin Li, James Dunn, and Albert L. Osterheld

Lawrence Livermore National Laboratory, Livermore, California 94550, USA

Alexander Ryabtsev and Sergey Churilov

Institute of Spectroscopy, Troitsk, Moscow Region 142092, Russia.

Abstract. In this work we present measurements of the wavelengths of the nickel-like $3d^9$ 4d $^1S_0 \rightarrow 3d^9$ 4p $^1P_1$ X-ray laser line in several low-Z nickel-like ions ranging from yttrium (Z=39) to cadmium (Z=48). With the help of these laser results, we identify this line to very high accuracy in nonlasing plasmas from gallium (Z=31) to molybdenum (Z=42). The measured wavelengths are compared with optimized level calculations using the multi-configuration Dirac-Fock code of Grant et al. As an example, for yttrium, we calculate a wavelength of 240.2 Å, and measure wavelengths of 240.11 ± 0.30 Å in the lasing plasma and 240.135 ± 0.015 Å in the nonlasing plasma. Accurate values of these wavelengths are essential for performing plasma imaging and interferometry experiments with multilayer optics which use the X-ray laser to backlight other plasmas. These results also provide important atomic data which is currently missing about the energy of the 4d $^1S_0$ level in the Ni I sequence and help guide experimentalists who are looking for lasing in these materials for the first time. We also observe lasing on the nickel-like $3d^9$ 4f $^1P_1 \rightarrow 3d^9$ 4d $^1P_1$ X-ray laser line in Zr, Nb, and Mo and present measured wavelengths for these ions as well as predicted values for other nearby ions.

1. Introduction

Accurate knowledge of the lasing wavelengths is important for improving our understanding of the energy level structure for the laser ion and for developing applications of laboratory X-ray lasers that rely on multilayer optics which are designed to work at one wavelength. This is especially true for complex ions such as Ni-like where the $3d^9$ 4d $^1S_0$ upper laser level mixes with the ground state level and makes it very difficult to calculate the lasing wavelengths ab initio.

In this work we present measurements of the wavelengths of the nickel-like $3d^9$ 4d $^1S_0 \rightarrow 3d^9$ 4p $^1P_1$ X-ray laser line in several low-Z nickel-like ions ranging from yttrium (Z=39) to cadmium (Z=48). With the help of these laser results, we identify this line to very high accuracy in nonlasing plasmas from gallium (Z=31) to molybdenum (Z=42). The measured wavelengths are compared with optimized level calculations using a multi-configuration Dirac-Fock code. We also observe lasing on the nickel-like $3d^9$ 4f $^1P_1 \rightarrow 3d^9$ 4d $^1P_1$ X-ray laser line in Zr, Nb, and Mo and present measured wavelengths for these ions as well as predicted values for other nearby ions. This is a new class of laser line which has been observed for the first time and is driven by the photopumping mechanism [1].

2. Experiments and Calculations

The laser experiments were performed on the COMET Laser Facility at Lawrence Livermore National Laboratory (LLNL). To make these materials lase, we use a nsec pulse to preform and ionize the plasma followed by a psec pulse to heat the plasma [2]. The delay between the two pulses is 1.6 ns, and the maximum energy in each pulse is 5 J. The beams are focused to a 70 μm $\times$ 1.25 cm line on to the approximately 1 cm long slab targets.

The main diagnostics is an on-axis flat-field grating spectrometer coupled to a thinned-backside-illuminated charge-coupled device (CCD) camera. Each CCD pixel corresponds to approximately 0.17 to 0.20 Å across the range of the spectrometer from 144 to 330 Å.

In our X-ray laser experiments we observe lasing on the 4d $^1S_0 \rightarrow$ 4p $^1P_1$ transition in Ni-like Y, Zr, Nb, Mo, Pd, Ag, and Cd. Figure 1 shows an on-axis Mo spectrum with the strong 4d $^1S_0 \rightarrow$ 4p $^1P_1$ line lasing at 189 Å and the weaker 4f $^1P_1 \rightarrow$ 4d $^1P_1$ line lasing at 226 Å. We have measured gains of 21 cm^{-1} and 4 cm^{-1} for these two lines, respectively, by doing a series of measurements for different length targets. The wavelengths of the measured laser lines with their uncertainties are given in Table 1. The error bar given is determined by the accuracy of determining the peak of both the reference lines and the measured lines and is between 0.15 to 0.3 Å.

To estimate the wavelengths of the expected laser lines we used the multi-configuration Dirac-Fock (MCDF) atomic physics code [3] in the optimized level (OL) mode. The OL calculation of the 4d $^1S_0$ upper laser state included all the n = 4 even parity J = 0 states. We then did a separate extended average level (EAL) calculation of the n = 4 odd parity J = 1 states and subtracted the energies to obtain the energy of the 4d $^1S_0 \rightarrow$ 4p $^1P_1$ transition. We then adjusted the calculated energies by 1.03 eV to bring the calculation at Nd into

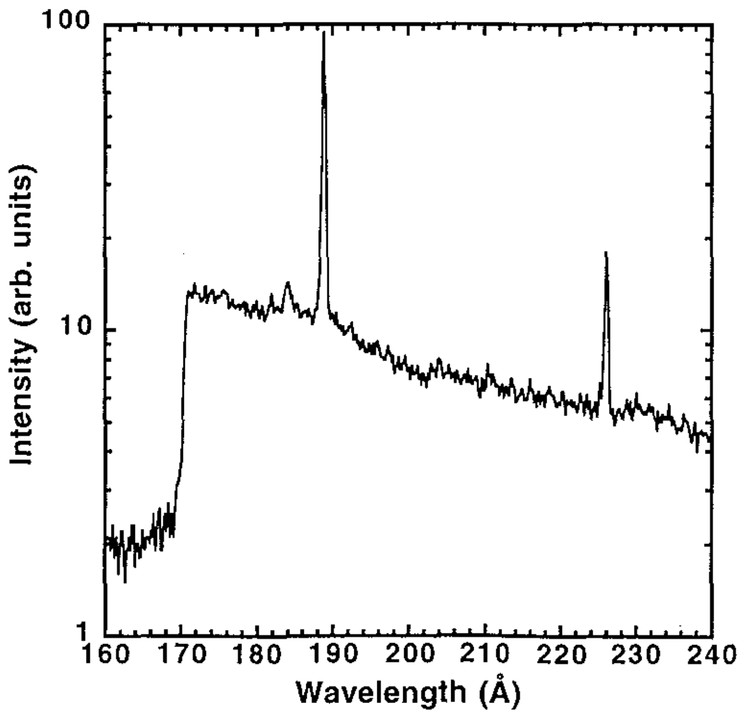

Fig. 1. Ni-like Mo spectrum shows lasing at 189 and 226 Å.

Table 1. Wavelengths (in Å) of the 4d $^1S_0 \rightarrow$ 4p $^1P_1$ and 4f $^1P_1 \rightarrow$ 4d $^1P_1$ transition in Ni-like ions with Z=31 to 60. The uncertainty in the last digit is given in parentheses.

Z	4d $^1S_0 \rightarrow$ 4p $^1P_1$			4f $^1P_1 \rightarrow$ 4d $^1P_1$	
	OL prediction	Laser measurement	Non laser measurement	Laser measurement	Calculated from Experimental energies
31			840.950(5)		
32			642.974(5)		
33			519.437(5)		
34			435.1(4)		
35			374.174(5)		
36			328.35(20)		
37			292.490(5)		383.9(2)
38			263.71(15)		337.1(2)
39	240.2	240.11(30)	240.135(15)		300.4(2)
40	220.0	220.20(30)	220.290(15)	271.0(2)	270.8(5)
41	202.9	203.34(30)	203.480(15)	246.4(3)	246.5(5)
42	188.3	188.95(30)	188.930(15)	226.0(3)	226.1(5)
43	175.5				
44	165.2				194.8(10)
45	155.3				181.1(10)
46	146.5	146.79(15)			170.6(10)
47	138.6	138.92(15)			160.4(10)
48	131.4	131.66(15)			
49	124.9				
50	119.0				
51	113.6				
52	108.7				
53	103.9				
54	99.65				
55	95.64				
56	91.90				
57	88.40				
58	85.10				
59	82.00				
60	79.06				

agreement with the measured value of this line at 79.06 Å. Our best estimate of the expected wavelengths for this line is seen in Table 1. It should be noted that a standard EAL calculation of all the n = 3 and 4 levels would give the energy of the 4d $^1S_0$ level that was too high by about 7 eV. We also were not able to get the calculations to converge for Z < 39.

Using the modest resolution measurements and the unambiguous identification of the 4d $^1S_0 \rightarrow$ 4p $^1P_1$ transition in lasing plasmas, we were able to identify this line in nonlasing plasmas from Ga to Mo. The experiments used either a vacuum spark or a laser produced plasma for the source with corresponding uncertainties in the measurement of 0.005 and 0.015 Å. The spectra were recorded on photographic plates using a 6.65 m vacuum spectrograph of normal incidence equipped with a spherical grating with 1200 lines per mm.

In the original analysis of the data years ago it was difficult to correctly identify the 4d $^1S_0 \rightarrow$ 4p $^1P_1$ line due to the large differences between theory and experiment for the energy of the 4d $^1S_0$ level. Using the unambiguous identification of this line in the laser plasma for Z = 39 to 42 we were able to identify the line in the nonlasing plasma to very high accuracy. By then comparing the calculated versus the measured energies for this transition, which are shown in Table 2, we were able to identify this line in the lower Z ions. For Se, Kr, and Sr, the wavelengths are interpolated using the measured values of the adjacent Z's and are included in Table 1 with larger error bars. More details of the experiments and calculations can be found in Ref. 4.

For the 4f $^1P_1 \rightarrow$ 4d $^1P_1$ line we used the energy level structure inferred from the spectral measurements of other lines to estimate the wavelength shown in Table 1.

Table 2. Energies (in cm^{-1}) of the Ni-like 4d $^1S_0 \rightarrow$ 4p $^1P_1$ transition.

Z	Observed	Calculated	Difference
Ga IV	118913	122968	4055
Ge V	155527	161575	6048
As VI	192516	199792	7276
Se VII	<229850>	238150	<8300>
Br VIII	267255	276317	9062
Kr IX	<304560>	314358	<9800>
Rb X	341892	352223	10331
Sr XI	<379200>	389902	<10700>
Y XII	416432	427529	11097
Zr XIII	453947	465077	11130
Nb XIV	491449	502606	11157
Mo XV	529297	540240	10943

3. Conclusions

In this work we present measurements of the wavelengths of the nickel-like $3d^9$ 4d $^1S_0 \rightarrow 3d^9$ 4p $^1P_1$ X-ray laser line in several low-Z nickel-like ions ranging from yttrium (Z=39) to cadmium (Z=48). With the help of these laser results, we identify this line to very high accuracy in nonlasing plasmas from gallium (Z=31) to molybdenum (Z=42). The measured wavelengths are compared with optimized level calculations using a multi-configuration Dirac-Fock. We also observe lasing on the nickel-like $3d^9$ 4f $^1P_1 \rightarrow 3d^9$ 4d $^1P_1$ X-ray laser line in Zr, Nb, and Mo and present measured wavelengths for these ions as well as predicted values for other nearby ions. This is a new class of laser line which is driven by the photopumping mechanism.

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